# RESEARCH

# COMBUSTION ENHANCEMENT BY INDUCED RAYLEIGH INSTABILITY

FINAL REPORT
BY
BRITISH COLUMBIA RESEARCH COUNCIL

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## TABLE OF CONTENTS


| | | Page |
|---|---|---|
| 1.0 | SUMMARY | 1 |
| | SOMMAIRE | 4 |
| 2.0 | INTRODUCTION | 7 |
| | 2.1 BACKGROUND | 7 |
| | 2.2 OBJECTIVES | 9 |
| | 2.3 STAFF | 9 |
| 3.0 | MATERIALS AND EQUIPMENT | 10 |
| 4.0 | RESULTS AND DISCUSSION | 12 |
| | 4.1 EVOLUTION OF EXPERIMENTAL PROCEDURES AND SYSTEM | 12 |
| | 4.1.1 Safety Switch and Ducting | 12 |
| | 4.1.2 Fuel Delivery Pressure | 13 |
| | 4.1.3 Electrical Charging and Insulation | 13 |
| | 4.1.4 Ignition Electrodes | 14 |
| | 4.1.5 Burner Tube | 15 |
| | 4.1.6 Spray Nozzle | 16 |
| | 4.2 COMBUSTION TESTING | 17 |
| | 4.3 RESULTS OF TESTS AFTER COMPLETION OF MODIFICATION | 17 |
| | 4.4 CURRENT REQUIREMENT FOR DROPLET INSTABILITY | 19 |
| | 4.5 ELECTROSTATIC EFFECTS | 20 |
| | 4.6 ALTERNATIVE SYSTEMS | 20 |
| | 4.7 POTENTIAL FOR ENHANCED COMBUSTION BY INDUCED RAYLEIGH INSTABILITY | 22 |
| 5.0 | CONCLUSIONS AND RECOMMENDATIONS | 23 |
| 6.0 | REFERENCES | 24 |

## TABLE OF CONTENTS (CONT'D)

Page

### LIST OF TABLES


Table 1 RESULTS OF FURNACE COMBUSTION WITH NO APPLIED VOLTAGE 27
Table 2 RESULTS OF FURNACE COMBUSTION TESTS WITH APPLIED VOLTAGE 28


### LIST OF FIGURES


Figure 1 EXPERIMENTAL SYSTEM . . . . . 29
Figure 2 EXPERIMENTAL EQUIPMENT AND INSTRUMENTATION . . . . . 30
Figure 3 DETAIL OF FUEL LINE INSULTATION . . . . . 31
Figure 4 BURNER ASSEMBLY . . . . . 32
Figure 5 ATOMIZING NOZZLE . . . . . 33


### LIST OF APPENDICES


Appendix 1 NOVA MODEL 370 FLUE GAS ANALYZER SPECIFICATIONS . . . 34
Appendix 2 CHARGE ON A SINGLE DROP OF FUEL . . . . . 35
Appendix 3 RAYLEIGH INSTABILITY CRITERION . . . . . 36
Appendix 4 CURRENT LEAKAGE THROUGH NO. 2 FUEL OIL . . . . . 37

## 1.0 SUMMARY

This report presents a review of literature on atomization by induced Rayleigh instability and reports the results of attempts to modify a commercial oil furnace burner to improve combustion by electrical charging of fuel droplets.

The objective of the present work was to investigate the practicality of improving combustion efficiency of a domestic oil furnace by imposing an electrostatic charge on the fuel droplets. During evaporation of a charged droplet, the charge to mass ratio increases until electrostatic repulsion forces overcome the cohesion (surface tension) of the droplet. This results in disintegration of the droplet into smaller particles. Conceptually, the large surface area of such highly atomized fuel leads to faster evaporation rates, more intimate mixing with combustion air, and higher combustion efficiencies.

Test results and observations clearly indicate that all attempts to charge oil droplets to the threshold of Rayleigh instability in the furnace burner were unsuccessful.

Modifications of the furnace systems were made in order to allow for continuous operation of the furnace and to electrically insulate the atomizing nozzle for electrostatic charge imposition.

The air circulating system was enlarged to accommodate larger volume flows of heated air. Ignition and flame detector systems were eliminated, since they interfered with application of charge to the nozzle, and pressure in the fuel delivery system was lowered to provide for larger droplets of atomized fuel as a base case.

The burner assembly was extensively modified in order to electrically insulate the nozzle from the rest of the furnace. A ceramic spacer was installed in the fuel line, the metal nozzle supporting structure was replaced with teflon, a glass spacer was installed in the air tube and later the whole air tube was refabrictated in glass. Several sharp needles were embedded in the sintered brass filter of the atomizing

nozzle. The pressure swirl component of the burner was retained. The charge was applied directly to the atomizing nozzle. This configuration was essentially a diode; with the nozzle acting as an emitting electrode, while the flame front and firepot walls functioned as collecting electrodes.

With these modifications a potential of 7kV could be applied to the nozzle without electrical arc discharge, at least in the initial periods of operation. After deposition of soot on the burner parts, the potential which could be sustained without discharge dropped to below 1kV.

At the conditions of no arc discharge, the measured current in the system was 3 microamperes. Calculation of charge carried by one droplet at these conditions yielded a two orders of magnitude lower value than necessary for the Rayleigh instability to occur.

Comparison of measured combustion characteristics (flue gas oxygen, carbon dioxide, carbon monoxide, temperature, smoke number) and the derived combustion efficiency for experiments with and without applied electostatic charge show the effect of the charge to be insignificant.

Results of the literature review indicated that for successful electrostatic charging of fuel oil, an atomizing nozzle requires incorporation of an emitting electrode with numerous sharp points and a second electrode in close proximity, both being submerged in the fuel oil to be charged. Sharp points were incorporated into the modified test burner, but its metal construction precluded use of a triode system. Housing of a triode atomizer would have to be made of nonconductive refractory material.

In general, the literature review indicated that research on induced Rayleigh instability has been largely focussed on development of spraying systems without regard to the finer droplet sizes required for fuel atomization.

## SOMMAIRE

Ce rapport est le résultat d'une revue de la littérature concernant l'atomisation induit par l'instabilité Rayleigh. Il rapporte aussi sur des essais qui ont pour but d'améliorer la combustion d'une fournaise à l'huile domestique, à laquelle on a apporté des modifications. Tous les essais ont été faits sur des gouttelettes de combustible.

L'objectif de ce travail était de rechercher les aspects pratiques nécessaire pour améliorer l'efficacité de la combustion d'une fournaise à l'huile domestique. L'attentat a été fait en appliquant une charge électrostatique sur les gouttelettes de carburant. La raison arithmétique entre la charge et le poids a augmenté jusqu' au point où les forces répulsives ont surmonté la cohésion (tension de surface), durant l'évaporation des gouttelettes chargées. Ceci a eu pour résultat de désintégrer les gouttelettes en plus petites particules.

Les résultats ainsi que les observations indiquent, clairement, que toutes tentatives de chargé electriquement, les gouttelettes d'huile au seuil de l'instabilité Rayleigh dans le brûleur de la fournaise, ont échouées.

Conceptuellement, les grandes surfaces des particules hautement atomisées de carburant mènent à des taux d'évaporation rapide; à un mélange avec l'air combustible plus intime; ainsi qu'à des efficacités de combustion plus elevées.

Plusieurs des systèmes fonctionnels de la fournaise ont dû être modifiés pour assurer l'opération continuelle de la fournaise et pour isoler, électriquement, l'atomisateur pour y imposer une charge électrostatique.

Le système circulatoire a été élargi pour accomoder de plus grands volumes d'air chauffé. On a éliminé les systèmes d'allumage et de détecteur de flamme puisqu'ils interféreraient avec l'application de la charge au jet atomisateur. Pour créer de plus grosses gouttelettes on a réduit la pression du système délivrant le carburant au jet atomisateur.

On a modifié grandement l'assemblage du brûleur pour isoler électriquement le jet atomisateur du reste de la fournaise. Un écarteur céramique a été installé dans la ligne du carburant. Le support du jet de métal a été remplacé par un support de teflon. Un écarteur de verre a été installé dans le tube d'air. Plus tard, on a remplacé complètement le tube d'air avec un tube fait de verre. Plusieurs aiguilles pointues ont été enfouies dans le filtre de brasse fritter du jet atomisateur.

L'assemblage tourbillon à pression du brûleur est resté intact. La charge électrique a été appliquée directement au jet atomisateur. Ceci est la configuation d'une diode; avec le jet atomisateur agissant comme une électrode émettrice, et le devant de la flamme et le compartiment brûleur agissant comme électrode réceptive.

Durant la période d'opération initiale et avec ces modifications, un potentiel de 7 kV pouvait être appliqué au jet atomisateur sans produire d' arc de décharge électrique. Lors de l'encrassement des parties du brûleur, le potentiel qui pouvait être soutenu sans produire d'arc de décharge électrique, était de moins que 1 kV.

Sans arc de décharge électrique la measure du courant dans le système était de 3 microampères. Les calculs de la charge sur une gouttelette sous ces conditions étaient cents fois plus bas que le seuil requis pour l'instabilité Rayleigh.

Une comparaison des charactéristiques de combustion (l'oxygène dans le gaz de fumé, le monoxide et dioxide de carbone, la température et l'index de fumé) avec celles de l'efficacitée de combustion expérimentale, avec ou sans charge électrostatique appliquée, indique que l'effet de la charge est non-significative.

La revue de la littérature indique que pour avoir du succès à charger le carburant électrostatiquement, le jet atomisateur doit être incorporé d'une électrode émettrice muni de plusieurs pointes aiguisées et d'une deuxième électrode qui est très près. Les deux doivent être submergés dans le carburant pour être chargé. Des aiguilles pointues ont été incorporées dans le brûleur d'essais mais la construction métale du brûleur ne permettait pas l'usure d'un système de triode. L'enclos d'un atomisateur triode devrait être fabriqué d'un matériel réfractaire, non conducteur.

La revue de la littérature nous indique que la recherche sur l'instabilité Rayleigh induit, est centré sur le système atomisateur sans aucun égard à l'application pratique à un système de combustion existant ou expérimental.

# 2.0 INTRODUCTION

## 2.1 BACKGROUND

Combustion of liquid fuels is one of the most important methods of energy generation. A variety of burners and engines use liquid fuels to convert energy of combustion to other forms of energy. Their combustion efficiency is of utmost importance for overall effectiveness of energy generation processes. The combustion efficiency can be improved effectively by increasing the fuel evaporation rate into the combustion air stream. Under otherwise equivalent conditions this rate is directly proportional to the fuel surface area. Thus a number of atomizing devices have been developed for different applications, to render the fuel droplets small and to provide for efficient mixing with combustion air.

Conceptually, a disruption of liquid droplets by electrostatic forces could, for a small energy expediture, enhance fuel atomization and thus be an effective method of combustion efficiency improvement. As early as 1882, Lord Rayleigh [1] theoretically predicted that an upper limit exists for an amount of charge on a droplet before it becomes unstable, disintegrating into a number of smaller droplets. Eighty years later, Hendricks and Schneider [2] presented the derivation of the stability theory in detail, in complete agreement with Lord Rayleigh's conclusions. Other theoretical assessments have also appeared [3, 4].

Doyle et al. [5] verified this prediction and found that an evaporating charged droplet 60-200 microns in diameter becomes unstable as its charge per surface area increases, until finally one or more small highly charged droplets are ejected and the parent droplet loses about 30% of its charge. This ejection of smaller droplets occurs several times during a lifetime of the parent droplet.

Practical application of the concept for enhanced combustion was attempted by Newgard and Noon [6] at about the same time. Some success was achieved in terms of demonstrating droplet instability at large droplet diameters and a number of critical problems were identified, particularly the need for such a high voltage that incipient air ionization results in current leakage from charged droplets.

Abbas and Latham [7] extended the work of Doyle et al. to smaller (30 microns) and larger (1 mm) droplets. Small droplets in their experiments behaved similarly to those in Doyle's et al., while large droplets lost their charge by corona discharge without mechanical disintegration.

Roth and Kelly [8] provided a theoretical treatment of the disruption of evaporating charged droplets. The theoretically predicted number of formed droplets, their mass, charge, and diameter ratios agree well with experimental values. Their theory predicts formation of a number of small "sibling" droplets, ~15 microns in diameter, carrying ~5% of the parent droplet mass and ~25% of its charge.

In another paper [9], Kelly developed the basic descriptive equations for low charge density electostatic atomization. He found, that for droplets in the 10 micron and larger size range, the only requirement for a hydrocarbon liquid to be succesfully charge-sprayed is, that its viscosity is less than about 250 mPa.s.

True [10] discusses the charged fuel spray plume behaviour in the combustion region. The plume shape variations with varying spray parameters (background air density, droplet diameter and flow rate) are described in this paper.

Application of electrostatic atomization of hydrocarbons to combustion is the theme of another paper by Kelly [11] in which he discusses practical aspects of low charge density spraying [9] in the context of atomization of hydrocarbon fuels. In the second part of the paper, Kelly describes a "Spray Triode", which is an electrostatic spray device consisting of a fluid supply, a free charge supply and an emitter and a "blunt" electrodes. Flame front and combustion chamber walls serve as the third electrode of the Triode. This paper is based on a patent granted to Kelly earlier [12].

A number of other patents relating to electrostatic charging of hydrocarbon fuels include internal combustion engine applications [13-18] various types of burner applications [19-21] and a gas turbine application [22]. One patent was found dealing with removal of electrostatic charge from the fuel, claiming that a charge inhibits atomization [23].

From literature reviewed prior to and during the current study, it appears that only Newgard and Noon [6] generated actual combustion performance data of electrostatically atomized fuels.

## 2.2 OBJECTIVES

The objective of this study was to investigate the practicality of improving combustion efficiency of a domestic oil furnace, by electrostatic charge imposed on the fuel droplets.

## 2.3 STAFF

In the initial phases of the project Mr. Gordon Esplin was in overall charge while Dr. D. Sheraton was responsible for experimental work. The project was completed by Dr. R. McElroy and Mr. J. Jezko.

## 3.0 MATERIALS AND EQUIPMENT

Figure 1 shows the overall experimental system including furnace, instrumentation/control system and ducting. Figure 2 is a schematic of the test system.

A sufficient amount (3x200L) of No.2 fuel oil was obtained from Chevron Canada to ensure uninterrupted supply of oil of constant quality for the duration of the project.

MACOR machinable ceramic, for some of the insulation parts of the burner, was purchased from Duramic Products, Inc.

An AIRCO, Model AWTL-100, domestic oil furnace was purchased. Installation was done by a certified installer.

The electrostatic power supply, Model EPS 540, was manufactured by DeVilbiss Canada. This type of power supply is normally used for electrostatic spray-painting. High tension cables for use with this power supply are complete with all the necessary connections for spray-painting applications and are very expensive. For this project a high tension cable was manufactured from a length of 1/4" coaxial cable (RG59U). A similar cable was tested by B.C.Hydro High Tension Laboratory, Surrey, to withstand up to 100kV charge. The cable shielding was grounded together with the body and supporting structure of the furnace.

The fuel delivery pump pressure was initially measured by calibrated pressure transducer (Data Instruments, Model EA) connected to a chart recorder, and later, when the transducer was damaged by electrostatic discharge, by a 0-1400 kPa (0-200 psi) bourdon gauge.

The stack temperature was measured by a type K thermocouple with Omegatemp (Omega Engineering, Inc.) battery powered probe. On-line analysis of flue gas for oxygen, carbon dioxide and carbon monoxide was provided by NOVA 370 portable flue gas analyzer (Nova Analytical Systems, Inc.). Technical specifications of the NOVA instrument are presented in Appendix 1. Before analysis, the flue gas was passed through an ice cooled trap to remove moisture.

Smoke number was determined with a DWYER smoke gauge pump (Model #920).

The current and voltage measurements were provided by a microampere and kilovolt gauges built into the electrostatic power supply. The current gauge full scale is 200 microamperes with 5 microampere divisions while the voltage gauge reads 50 kV full scale with 5kV divisions.

# 4.0 RESULTS AND DISCUSSION

## 4.1 EVOLUTION OF EXPERIMENTAL PROCEDURES AND SYSTEMS

A number of modifications to the furnace air circulation, electrical, fuel delivery, and especially burner systems were neccessary to adapt the burner unit for charging of the oil while maintaining its structural integrity and gas flow characteristics. A test to ensure proper function of the furnace was carried out after each modification.

A description of the modifications to the furnace systems, approximately in chronological order, is presented in the following sections.

### 4.1.1 Safety Switch and Ducting

The operation of the furnace, as originally installed, was constantly interrupted by a safety switch after ~100 sec of operation. This on-off operation would make the determination of combustion characteristics (oxygen, carbon dioxide, carbon monoxide in flue gas, and smoke number) difficult, due to the transient periods at the start and end of the burning cycles. The problem was due to a small cross-sectional area (6" diameter) of the heated air duct. This led to small volume flow of heated air, causing overheating of the plenum in a short period of time, which in turn resulted in shutdown by a safety switch. When a large cross-section duct (12x18") was installed, a large volume flow of heated air prevented the plenum from overheating and unlimited uninterrupted operation of the furnace was ensured.

### 4.1.2 Fuel Delivery Pressure

The furnace burner is designed to operate most efficiently with fuel delivery pressure of 690 kPa (~100 psi) and with an excess combustion air adjusted to such a volume that smoke number does not exceed 1 on the Bacharach scale [26]. With these settings, the manufacturers claimed efficiency of the system is close to 87% [27]. When operated at optimum conditions, it would be difficult to observe any improvements in combustion characteristics of the furnace. On the advice of the Scientific Authority, the fuel delivery pressure was lowered to 80 psi, thus making the atomization less efficient, resulting in larger diameter droplets. Combustion air supply was also adjusted so that the smoke number read approximately 5 on the scale. Lowering of the fuel delivery pressure was achieved by an adjustment of a pressure regulating screw provided on the fuel delivery pump. In addition, a bypass valve was installed on the fuel line to allow lowering of the pressure still further.

### 4.1.3 Electrical Charging and Insulation

In order to impose a charge on the fuel droplets as they emerged from the burner spray nozzle it was neccessary to electrically insulate the nozzle. Initially, the nozzle was insulated from the rest of the system by a ceramic spacer inserted in the fuel line. The charge was brought to the nozzle tip by the teflon insulated high tension cable. The spacer was machined from a 2.54 cm diameter bar of MACOR machinable ceramic. Approximately 13 mm separation between metal tubing ends was provided (Figure 3). Macor ceramic was also used to make non-conductive legs to replace metal supporting structure holding the nozzle assembly in place inside the burner air tube (Figure 4).

These modifications proved to be inadequate, as an arc discharge was observed between the nozzle tip and retention head (Figure 4) when a charge was applied. After removing the retention head, discharge occured from the nozzle supporting structure to the burner air tube. The whole supporting structure was therefore replaced with one machined from a 2.54 cm thick Teflon sheet. The cross-sectional geometry of the original supporting assembly was retained in order to maintain a similar primary air flow pattern.

Operation of the furnace with these modifications resulted in incomplete combustion, excessive smoke and some combustion products being blown back past the burner. At first, an inadequate draft was suspected, so the stack was removed and checked for obstructions. Further tests showed that the problem was caused by removal of the retention head which plays an important role in providing a good mixing of fuel droplets and combustion air.

The retention head was therefore replaced and other measures to prevent occurence of arc discharge were implemented. A glass sheath in the form of a test tube with a 1/4" hole in the bottom (Figure 5) was fitted over the nozzle assembly. Tests with this arrangement showed not only that the arcing occurred despite the sheath protecting almost all the nozzle surface, but the sheath also interfered with fuel atomization, which resulted in incomplete combustion.

### 4.1.4 Ignition Electrodes

Close observation of the arc discharge revealed that it occured not only between the nozzle tip and air tube baffles, but also between the nozzle and the pointed ignition electrodes (Figure 4). First, it was thought that it would suffice to insulate these electrodes from the rest of the ignition circuit after the fuel was ignited. This was accomplished by

tipping the ignition transformer in order to break the contact between the electrodes and the rest of the system. Vinyl bellows were made to prevent the combustion air from blowing past the transformer. Also, a manual switch was incorporated into the flame detector circuit, since the flame detector pointed away from the flame when the transformer was lifted upwards. With this arrangement the furnace was ignited with the transformer pressure contacts in contact with the ignition electrodes and with the flame detector circuit closed. When the flame was established, the transformer was lifted, thus breaking the contact with the electrodes, and the flame detector circuit was interrupted, preventing the shut-down of the furnace. However, in further tests it was found that electric discharge still occured through the ignition electrodes. The electrodes were therefore eliminated completely and the ignition transformer was replaced with a cover made of aluminum sheet. From this point on, fuel was ignited with a burning wick thrown into the firepot.

### 4.1.5 Burner Tube

At this point it became apparent that along with insulation of the nozzle tip, the burner air tube would have to be electrically insulated as well. To insulate the air tube, it was shortened at the blower end and a 4 cm long piece replaced with a PVC pipe machined to exact dimensions to fit snuggly into the shortened air tube on one end and into the blower body on the other end.

A test with this configuration seemed to be encouraging at first, since at least 7kV charge could be applied to the nozzle tip without discharge occuring. However, the plastic extension deformed after the burner was switched off due to radiated heat from the firepot. The plastic extension was therefore replaced with a glass spacer with the same dimensions.

### 4.1.6 Spray Nozzle

Short lengths of sharp needles were embedded into the spray nozzle sintered brass filter (Figure 5) to provide local magnification of the electric field. This geometrical magnification of the surface electric field is needed to overcome 300 fold difference in electric breakdown strength of fuel oil (~ $2 \times 10^7$ V/m) and ~$5 \times 10^9$ V/m electric field strength needed to extract electrons from metallic surfaces [11].

Tests with these modifications revealed that, initially, a charge of ~7kV could be sustained on the nozzle tip. However, after a short period of operation, discharge was again observed between the nozzle and the air tube baffles, and between the end of the air tube and the blower assembly, across the glass spacer. The whole air tube was therefore replaced with an equivalent length of 10 cm (4") diameter glass tube.

Tests with this modification were only partially succesful.

Initially, a 7 kV charge could again be sustained, but after a short time, when some soot and oil covered the glass surface of the air tube, the sustained charge dropped to less than 1kV. Nevertheless, tests were carried out in the initial period, and readings of current, voltage, oxygen, carbon dioxide, carbon monoxide and smoke number were taken, both without and with the charge potential applied. Further readings were taken with the voltage increased to 10,15,20 and 24kV (maximum) even when arcing was observed at these settings, since it was thought that the fuel droplets could be at least partially charged in between arc discharges. The time period between discharges was about 1 sec at 7kV. At 24kV the time between discharges was so short that arcing appeared to be continuous.

## 4.2 COMBUSTION TESTING

At the start of each combustion test the fuel storage tank was filled, placed on an electronic scale, and connected. The furnace was then ignited and allowed to attain equilibrium conditions as indicated by a stable stack temperature. Readings of oxygen, carbon dioxide, carbon monoxide, temperature and smoke number were taken. If neccessary, adjustments to the combustion air intake were made, steady state conditions allowed to re-establish, and the next set of readings taken. After satisfactory values for all the parameters were established, a charging potential was applied to the nozzle. Generally, no observable change in any of the parameters occured, so a period of 10 minutes was chosen arbitrarily as a sufficient time to establish new steady state conditions. Readings of combustion parameters were then taken. Usually, before a new voltage level was applied, the system was allowed to operate without applied potential for 10 minutes and a new set of readings was taken. Frequently during the operation of the furnace, the flame was inspected visually through an observation door. Visual inspection during operation with applied potential allowed observation of the path of arc discharge when it occured.

An average fuel consumption was determined by weight loss of the storage tank over a fixed time period. Volumetric consumption was calculated using a value of 0.826 $g/cm^3$ for No. 2 fuel oil [25].

## 4.3 RESULTS OF TESTS AFTER COMPLETION OF MODIFICATION

Only data pertaining to operation of the furnace with essentially all the modifications in place are reported here. These experimental data are summarized in Tables 1 and 2. The combustion efficiencies were obtained from the Table of Combustion Efficiencies for No. 2 Fuel Oil [25] by interpolation.

Table 1 presents data collected while the furnace was tested with different delivery pump pressure settings and air restrictions to establish the effects of these parameters on the combustion characteristics. In general, there are reasonable correlations between flue gas oxygen contents (i.e. excess combustion air) and: carbon dioxide, temperature, smoke number and combustion efficiency. The carbon monoxide data in the first test sequence do not correlate, and it seems probable that the sensor was disfunctional.

Table 2 lists experimental data obtained during operation at an oil delivery pressure of 560 kPa (80 psi) with and without voltage. These data indicate that effects of applied voltage on measured combustion characteristics were generally too small to be differentiated at the observed analytical precision. A possible exception is the slight but consistent deterioration in smoke number with charge applied in the second test. After shut-down, inspection of the furnace revealed that a lump of coke had formed in the firepot underneath the burner air tube tip. Droplets of fuel probably accumulated on the retention head or inside the air tube, dripped to the firepot and coked, producing excessive smoke in the process. In this test, the nozzle had been moved forward a fraction of an inch in an attempt to stop the accumulation of fuel oil in the (glass) air tube. The results show that the combustion air supply had to be increased to keep the smoke number down, resulting in higher stack temperatures and therefore lower combustion efficiencies. Even in this experiment, the applied charge did not result in noticeable change in combustion characteristics.

Results presented in Table 1 show that the furnace burner operates at quite high combustion efficiencies at all fuel delivery pump pressures tested. The requirement for low excess oxygen in the flue gas in order to maximize combustion efficiencies also causes excessive smoke and soot formation. It can be seen from the data that for similar excess oxygen levels the efficiency and smoke numbers are lower for

lower fuel pump delivery pressure. At 100, 80 and 70 psi the average fuel flow rates were 2656, 2460 and 2345 g/h respectively. The improved performance at lower delivery pressure is considered to be due to increased residence time in the combustion zone and/or heat exchanger which apparently more than compensates for reduced atomization efficiency at lower fuel pressure.

## 4.4 CURRENT REQUIREMENT FOR DROPLET INSTABILITY

For the conditions of no arc discharge (7kV, 3microamperes) a calculation of charge on a single drop (Appendix 2) yields approximately $2 \times 10^{-15}$ Coulomb/drop. For Rayleigh instability to occur the calculated minimum charge is $1.5 \times 10^{-13}$ Coulomb/drop (Appendix 3). Thus there was a two order of magnitude deficiency in charging the fuel droplets to attain Rayleigh instability. This calculation does not take into account a current leakage which must exist in a liquid with finite electrical conductivity. A calculation (Appendix 4) for No.2 fuel oil with conductivity of $150 \times 10^{-12}$ mho/m [8] yields a leakage current of approximately $2 \times 10^{-3}$ microamperes which is less than 0.1% of the observed current. However, this calculation is sensitive to uncertainty in the conductivity value. Specific conductivity of the fuel oil used was not determined. It can be seen that, at the conditions when no arc discharge from the nozzle tip was observed, the charge carried by fuel droplets was insufficient for Rayleigh instability to occur.

Under arc discharge conditions, i.e. voltage >7 kV, some fraction of the incremental current was presumably carried by the oil, but even at the maximum system voltage of 24 kV - when arcing was nearly continuous - the total current was still below the threshold value for Rayleigh instability.

This indicates that achievement of instability requires a completely non-conducting burner assembly to avoid extended arcing.

In this study the pressure swirl component of the nozzle permitted no modifications. As charge had to be brought directly to the nozzle tip, the proximity of the air tube baffles made the arc discharge unavoidable at voltages sufficient to attain significant current flow.

## 4.5 ELECTROSTATIC EFFECTS

In some tests with applied voltage, coke formation was noted in areas where discharge arcs terminated. This was tentatively attributed to electrostatic attractions of grounded surfaces for charged oil droplets.

This suggests that in any practical application of Rayleigh instability to oil combustion, vaporization would have to be virtually complete before the gas/droplet stream encounters the collector electrode. Othervise, electrostatic attraction between droplets and the collector electrode may lead to droplet aggregation and coking at the collector electrode.

## 4.6 ALTERNATIVE SYSTEMS

A different design of spray nozzle, claimed to be especially adapted to electostatic charge applications has been described by A. J. Kelly [11, 12]. This design incorporates a "Spray Triode" in which the active electrodes are submerged in an insulating fluid (fuel oil), and external corona break-down and arc discharge is precluded. Charging of the fluid is accomplished between a charged emitter electrode, incorporating a large number of submicron thickness tungsten filaments embedded in a nonconductive metal-oxide matrix, and a non-charged "blunt" electode. In another modification of the Spray Triode, the emitter electrode was manufactured from a large number of razor blade segments arranged in a cylinder around a metal rod or cylinder serving as a "blunt" electrode, with sharp edges pointing towards the blunt electrode. Both the filaments and the sharp edges of razor blades served as emitting zones

of the emitter electode. In combustion applications the flame front and combustion chamber would serve as a third electrode of the system. Tests with this electrode (non combustion) using a mineral oil shoved that a well defined spray behaviour was established at moderate charging voltage (7kV) [12].

From the results of Kelly's work, two drawbacks of the system used in this investigation are apparent. First, the test configuration was essentially a diode, with the nozzle containing an emitting electrode and the flame front as a collecting electrode. The second drawback is the way in which the charge is applied to the emitting electrode. The electrode body (nozzle) is not submerged in the fuel oil or otherwise fully insulated which leads to electric break-down of the surrounding atmosphere, resulting in arc discharge. On this basis, complete remanufacture of the burner system in electrically insulating materials would be required to avoid arcing with either diode or triode electrode arrangements.

Kelly, in his paper [11] and patent [12], while mentioning combustion applications, does not present an example of actual operation of his Triode in combustion experiments. In fact, in the literature collected [12-23] on the subject, no examples of actual operation of various devices described for use in combustion systems are given either.

In view of the above discussion it is evident that for successful application of electrostatic charge to fuel oil droplets a system must be manufactured, which will incorporate emitting electrode with numerous sharp points and a blunt electrode in close proximity, both of which will be submerged in the fuel oil to be charged. The housing for the electrodes will have to be made of a heat resistant nonconductive material. For conversion of existing combustion systems, such as domestic fuel oil fired furnaces, the electrodes will have to be incorporated into the design of the pressure swirl atomizer nozzle.

## 4.7 POTENTIAL FOR ENHANCED COMBUSTION BY INDUCED RAYLEIGH INSTABILITY

Current results indicate that oil charging to the Rayleigh limit cannot be obtained in a burner of primarily metal construction due to arcing. Other investigations have achieved atomization by induced Rayleigh instability, but the lack of documentation of improved combustion strongly suggests that this has not been attained.

The requirement of relatively low viscosity for Rayleigh instability limits its potential application to light liquid fuels for which quite good combustion efficiencies are attainable by mechanical atomization.

On this basis, further investigation of light liquid fuel atomization by induced Rayleigh instability would require:

- an application for which mechanical atomization efficiency is not acceptable.

- a burner system completely fabricated from electrically insulating materials, with all this implies in terms of forming/machining difficulties, fatigue resistance, etc.

No such application has been identified in the present investigation or the literature review, and the materials/fabrication requirements for the (hypothetical) burner assembly are formidable.

## 5.0 CONCLUSIONS AND RECOMMENDATIONS

Test results and observations clearly indicate that all attempts to charge oil droplets to the threshold of Rayleigh instability in the furnace burner were unsuccessful.

The level of oil droplet charging obtained at the threshold of arc generation was substantially below the Rayleigh limit and - at this level of charging - electrostatic aggregation of fuel droplets at grounded furnace surfaces has a deleterious effect on combustion efficiency.

The selection of a commercial oil burner/furnace as the test system was unwise due to its non-adaptability to requirements for electrical charging of fuel oil.

Successful application of Rayleigh instability to a combustion system would require a radically different burner design involving primarily non-conducting materials to eliminate short path arcing.

In view of the (relatively) good atomization/combustion efficiency attainable with currently available mechanical atomizers, there is only a small potential margin for performance improvement. For open combustion as in a furnace, current results indicate that marginal performance improvement might be achieved by the simplistic approach of reducing fuel-air flows (i.e. effectively de-rating) to obtain longer combustion zone and heat exchanger residence time.

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TABLE 1

RESULTS OF FURNACE COMBUSTION TESTS WITH NO APPLIED VOLTAGE
Fuel Delivery Pressure 100 psi

| DELIVERY PRESSURE (kPa) | FUEL FLOW RATE (g/hr) | OXYGEN (Vol 1%) | CARBON DIOXIDE (Vol 1%) | FLUE GAS CARBON MONOXIDE (ppm) | STACK TEMPERATURE (°C) | SMOKE NUMBER | COMBUSTION EFFICIENCY (%) |
|---|---|---|---|---|---|---|---|
| 700 | 2656 | 5.7 | 13.9 | 10 | 219 | 0 | 84.8 |
| | | 3.7 | 13.8 | 15 | 205 | 1 | 86.4 |
| | | 3.1 | 14.4 | 8 | 200 | 4 | 86.8 |
| | | 3.1 | 15.5 | 5 | 203 | 5 | 86.7 |
| | | 2.5 | 15.0 | 8 | 192 | 7 | 87.3 |
| | | 1.9 | 15.4 | 8 | 187 | 9 | 87.7 |
| 560 | 2460 | 5.1 | 13.2 | n/d | 200 | 0 | 86.0 |
| | | 4.1 | 13.9 | n/d | 190 | 1 | 86.9 |
| | | 3.5 | 14.6 | n/d | 184 | 4 | 87.4 |
| | | 2.0 | 16.4 | n/d* | 173 | >10 | 88.3 |
| 490 | 2345 | 4.9 | 13.0 | n/d* | 188 | 0 | 86.4 |
| | | 4.4 | 13.6 | n/d | 182 | 1 | 87.0 |
| | | 3.8 | 14.0 | n/d | 178 | 4 | 87.6 |
| | | 3.3 | 15.0 | n/d | 168 | 4 | 88.2 |

n/d = not determined (damaged CO sensor)

TABLE 2

RESULTS OF FURNACE COMBUSTION TESTS WITH APPLIED VOLTAGE

| DELIVERY PRESSURE (kPa) | FUEL FLOW RATE (g/hr) | VOLTAGE (kV) | CURRENT (μA) | OXYGEN (Vol %) | CARBON DIOXIDE (Vol %) | FLUE GAS CARBON MONOXIDE (ppm) | STACK TEMPERATURE (°C) | SMOKE NUMBER | COMBUSTION EFFICIENCY (%) |
|---|---|---|---|---|---|---|---|---|---|
| 80 | 2509 | 0 | 0 | 4.5 | 13.8 | 6 | 194 | 8 | 86.6 |
| | | 0 | 0 | 5.8 | 12.9 | 3 | 208 | 4 | 85.2 |
| | | 0 | 0 | 5.6 | 13.0 | 6 | 206 | 5 | 85.4 |
| | | 7 | 3 | 5.6 | 12.8 | 6 | 206 | 5 | 85.4 |
| | | 20 | 130 | 5.7 | 12.7 | 6 | 207 | 5 | 85.3 |
| | | 10 | 38 | 5.6 | 12.8 | 8 | 206 | 5 | 85.4 |
| | | 20 | 130 | 5.7 | 12.8 | 9 | 206 | 5 | 85.4 |
| 80 | 2512 | 0 | 0 | 5.7 | 12.4 | 5 | 207 | 6 | 85.3 |
| | | 0 | 0 | 5.5 | 12.6 | 4 | 205 | 7 | 85.6 |
| | | 10 | 35 | 5.4 | 12.7 | 6 | 205 | 8 | 85.6 |
| | | 20 | 130 | 5.5 | 12.7 | 6 | 205 | 8 | 85.6 |
| | | 0 | 0 | 5.5 | 12.7 | 5 | 205 | 8 | 85.6 |
| | | 20 | 130 | 5.5 | 12.7 | 7 | 204 | 8 | 85.6 |
| | | 0 | 0 | 5.6 | 12.6 | 6 | 205 | 8 | 85.6 |
| 80 | 2508 | 0 | 0 | 7.3 | 11.2 | 11 | 241 | 6 | 83.3 |
| | | 0 | 0 | 7.7 | 10.8 | 19 | 243 | 5.5 | 82.2 |
| | | 0 | 0 | 7.7 | 10.7 | 20 | 243 | 6 | 82.2 |
| | | 7 | 3 | 7.7 | 10.7 | 20 | 243 | 6 | 82.2 |
| | | 10 | 40 | 7.7 | 10.8 | 20 | 243 | 6 | 82.2 |
| | | 15 | 79 | 7.6 | 10.7 | 20 | 242 | 6 | 82.3 |
| | | 20 | 130 | 7.7 | 10.7 | 20 | 243 | 6.5 | 82.2 |
| | | 24 | 148 | 7.7 | 10.8 | 20 | 243 | 6.5 | 82.2 |
| | | 0 | 0 | 7.8 | 10.7 | 20 | 242 | 6.5 | 82.3 |
| | | 7 | 11 | 7.7 | 10.8 | 20 | 243 | 6.5 | 82.2 |

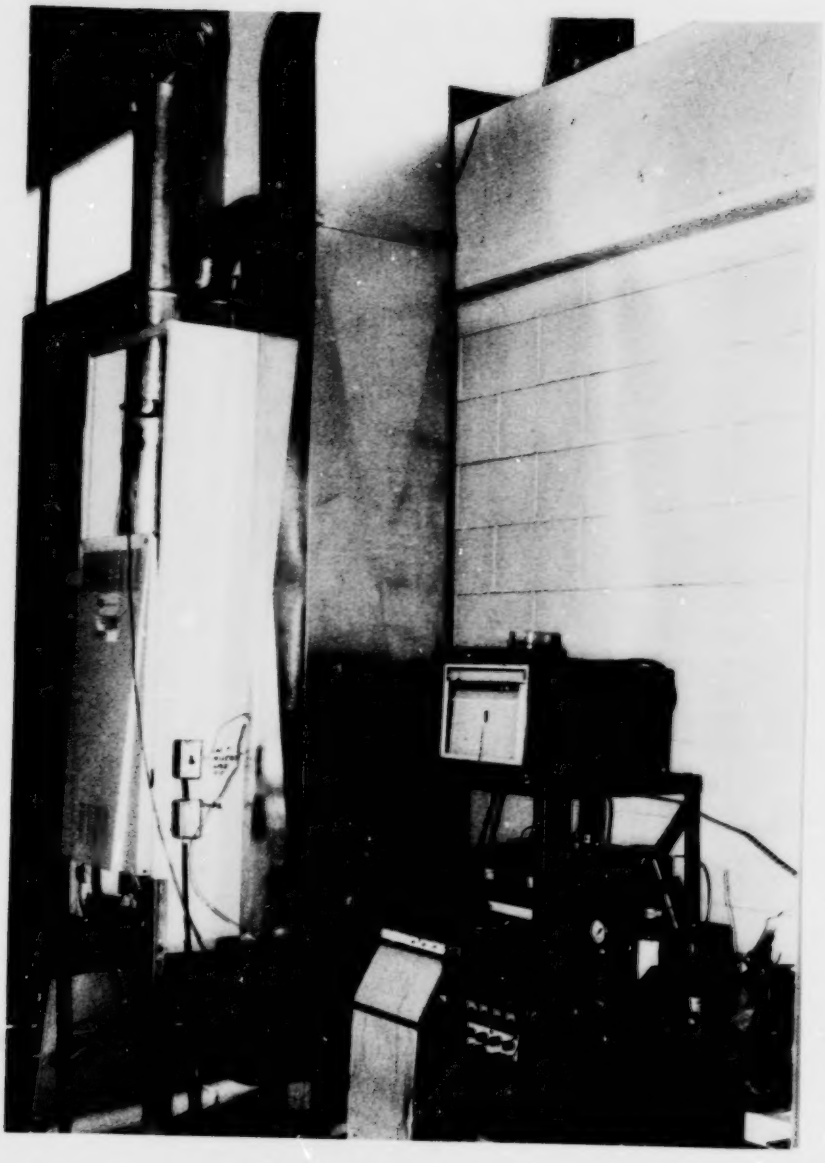


**FIGURE 1**
**EXPERIMENTAL SYSTEM**
(25847.9)

**FIGURE 2**

EXPERIMENTAL EQUIPMENT AND INSTRUMENTATION

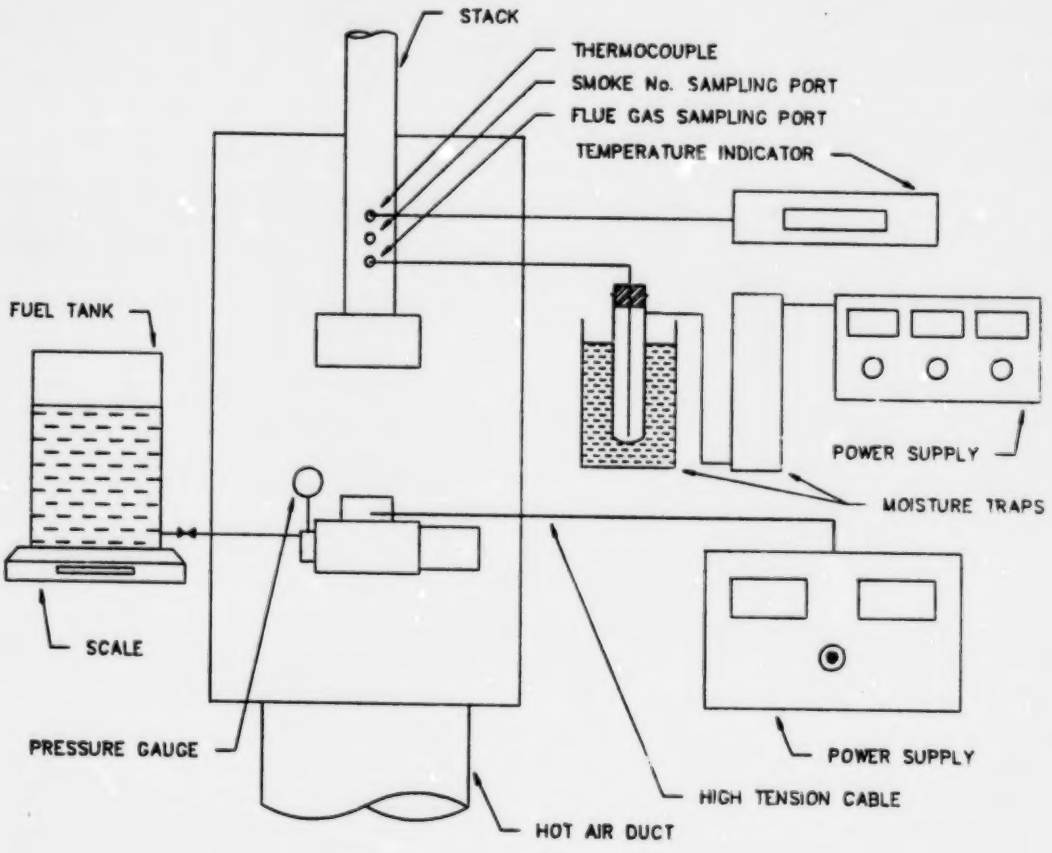


**FIGURE 3**

DETAIL OF FUEL LINE INSULATION

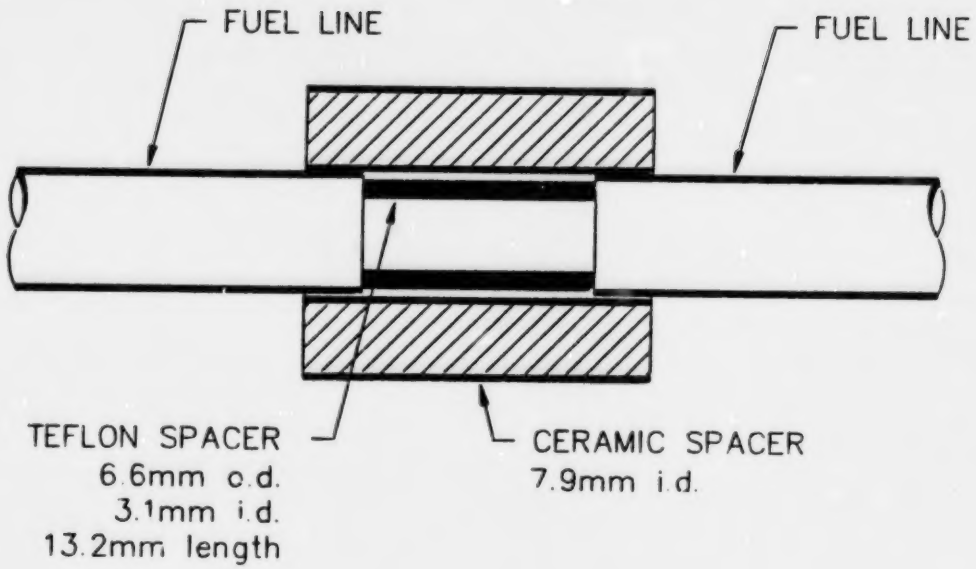


**FIGURE 4**

BURNER ASSEMBLY

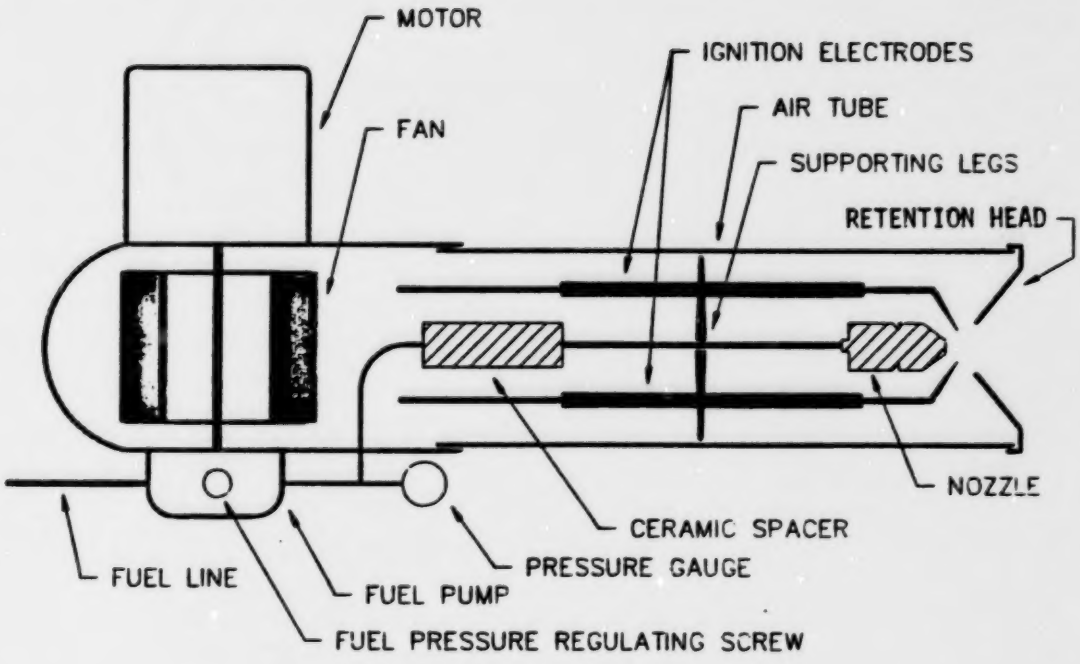
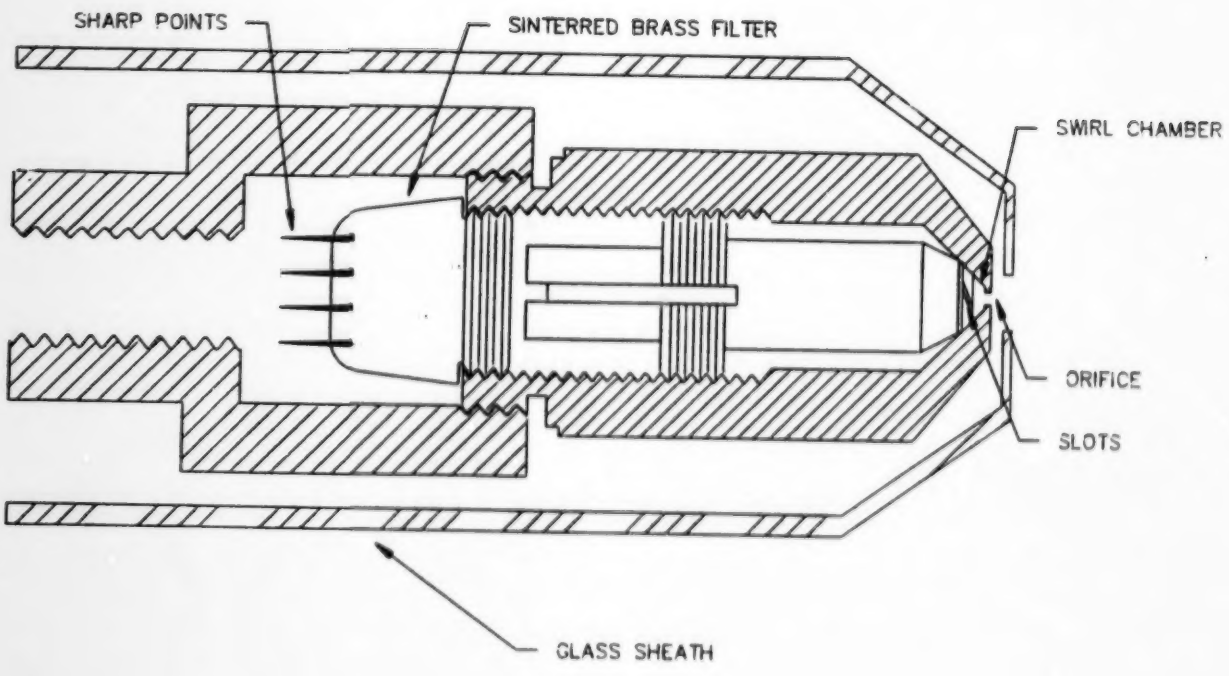


**FIGURE 5**

ATOMIZING NOZZLE



## APPENDIX 1

### Nova Model 370 Flue Gas Analyzer Specifications

| | |
|---|---|
| Method of Detection: | Customer replaceable electrochemical oxygen and CO sensors. Thermal conductivity sensor for $CO_2$. |
| Ranges: | 0-35% oxygen 0-2000 ppm and 0-4% CO, switch selectable 0-20% $CO_2$. |
| Displays: | LCD digital with switchable backlighting. |
| Accuracy and Repeatibility: | Within $\pm$ 0.1% $O_2$ and $CO_2$, $\pm$ 10 ppm CO. |
| Drift: | 1% full scale per 8 hours of continuous operation. |
| Response Time: | 5-8 seconds. |
| Operating Temperature Range: | 0-40°C. |

## APPENDIX 2

### Charge on a Single Drop of Fuel

Assume: Drop diameter $10 \times 10^{-6}$ m. No current leakage due to fuel conductivity.

Current: 3 microamperes = $3 \times 10^{-6}$ Coulomb/sec

Mass flow rate: 2509 g/hr

---

Volumetric flow rate: mass flow rate/density

density = 141.5/(API + 131.5) [22] = 141.5/32.5 + 131.5 = 0.862 $g/cm^3$

volumetric flow rate = 2509/0.862 = 2912 $cm^3/hr$ = 8.088x10exp-7 $m^3/sec$

Drops flow rate: Volumetric flow rate/drop volume

drop volume = $4/3\ \pi\ r^3 = 4/3\ \pi\ (10^{-15})/8$
= $5.236 \times 10^{-16}\ m^3$

drops flow rate = $8.088 \times 10^{-7}/5.236 \times 10^{-16} = 1.545 \times 10^9$ drops/sec

Charge on 1 drop: current/drops flow rate

charge/drop = $3 \times 10^{-6}/1.545 \times 10^9$
= $2 \times 10^{-15}$ Coulomb

## APPENDIX 3

### Rayleigh Instability Criterion

Assume: Drop diameter $10 \times 10^{-6}$ m.

Condition for instability:

Q..... charge in statcoulombs (1 statcoulomb = $3.336 \times 10^{-10}$ Coulomb)

$\alpha$..... tension in dynes/cm

r..... diameter of drop in cm

For No.2 fuel oil $\alpha$: = 0.031 dynes/cm, r = $5 \times 10^{-4}$ cm

$r = 5 \times 10^{-4}$ cm

$Q = 4.4$ statcoulomb = $1.5 \times 10^{-13}$ Coulomb

## APPENDIX 4

### Current Leakage Through No.2 Fuel Oil

For fuel line insulating spacer (Figure 1)

Fuel element cross sectional area = $2.25 \times 10^{-5}$ m

No. 2 fuel oil conductivity [2] = $1.5 \times 10^{-10}$/mho/meter

Resistance of fuel element = (conductivity/area x length)
= $3.9 \times 10^{12}$ Ohm

Current = voltage/resistance

Applied voltage = $7 \times 10^{3}$ V

Current = $7 \times 10^{3}/3.9 \times 10^{12} = 2 \times 10^{-3}$ microamperes